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MRI Predictors of Posterolateral Corner Instability: A Decision Tree Analysis of Patients with Acute Anterior Cruciate Ligament Tear

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Abstract: Purpose To determine the diagnostic performance of MRI for helping to predict posterolateral knee instability in patients with acute anterior cruciate ligament (ACL) tear. Materials and Methods This retrospective cohort study was performed in a consecutive series of 162 patients (mean age, 32.8 years ± 10.0 [standard deviation]; 95 men [mean age, 31.0 years ± 9.6] and 67 women [mean age, 35.4 years ± 10.0]) who underwent ACL reconstruction with (n = 19) or without (n = 143) concomitant posterolateral corner (PLC) reconstruction between June 2014 and February 2017. MR images were evaluated by two radiologists. Diagnostic performance of imaging findings was calculated. Clinical evidence of posterolateral instability requiring PLC reconstruction served as reference standard. The most significant predictors of posterolateral instability were determined with decision tree analysis. Results In patients with and without PLC reconstruction, respectively, the lateral collateral ligament was completely torn in 10 of 19 (52.6%) and seven of 143 (4.9%) patients; the posterior cruciate ligament in two of 19 (10.5%) and five of 143 (3.5%) patients; the popliteus tendon in three of 19 (15.8%) and none of 143 (0%) patients; and the biceps femoris tendon in four of 19 (21.1%) and none of 143 (0%) patients (data for reader 1). The smaller structures of the PLC were not constantly viewable. Complete tear or avulsion of the lateral collateral ligament was more frequent in patients who needed PLC reconstruction ($P < .001$), and decision tree analysis revealed that this finding was the most statistically significant predictor of posterolateral instability. Instability was correctly predicted in 147 of 162 patients (90.7%) by reader 1 and 151 of 162 patients (93.2%) by reader 2. Conclusion Complete tear or avulsion of the lateral collateral ligament was the most significant predictor at MRI of posterolateral instability. Assessment of the smaller posterolateral corner structures did not improve diagnostic performance.

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MRI Predictors of Posterolateral Corner Instability: A Decision Tree Analysis of Patients with Acute Anterior Cruciate Ligament Tear

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Conflicts of interest are listed at the end of this article.

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Materials and Methods: This retrospective cohort study was performed in a consecutive series of 162 patients (mean age, 32.8 years ± 10.0 [standard deviation]; 95 men [mean age, 31.0 years ± 9.6] and 67 women [mean age, 35.4 years ± 10.0]) who underwent ACL reconstruction with (n = 19) or without (n = 143) concomitant posterolateral corner (PLC) reconstruction between June 2014 and February 2017. MR images were evaluated by two radiologists. Diagnostic performance of imaging findings was calculated. Clinical evidence of posterolateral instability requiring PLC reconstruction served as reference standard. The most significant predictors of posterolateral instability were determined with decision tree analysis.

Results: In patients with and without PLC reconstruction, respectively, the lateral collateral ligament was completely torn in 10 of 19 (52.6%) and seven of 143 (4.9%) patients; the posterior cruciate ligament in two of 19 (10.5%) and five of 143 (3.5%) patients; the popliteus tendon in three of 19 (15.8%) and none of 143 (0%) patients; and the biceps femoris tendon in four of 19 (21.1%) and none of 143 (0%) patients (data for reader 1). The smaller structures of the PLC were not constantly viewable. Complete tear or avulsion of the lateral collateral ligament was more frequent in patients who needed PLC reconstruction (P < .001), and decision tree analysis revealed that this finding was the most statistically significant predictor of posterolateral instability. Instability was correctly predicted in 147 of 162 patients (90.7%) by reader 1 and 151 of 162 patients (93.2%) by reader 2.

Conclusion: Complete tear or avulsion of the lateral collateral ligament was the most significant predictor at MRI of posterolateral instability. Assessment of the smaller posterolateral corner structures did not improve diagnostic performance.

Online supplemental material is available for this article.

Posterolateral corner (PLC) injuries of the knee most often result from high-energy trauma and are commonly associated with cruciate ligament tears (1–4). Clinical examination is the reference standard for the detection of posterolateral instability (1,5–10) but may be difficult in the setting of acute trauma because of the patient's knee pain, joint effusion, and diffuse tissue swelling (3). However, early diagnosis and treatment of PLC injury is crucial because untreated posterolateral instability is associated with poor clinical outcome, increases the risk for anterior cruciate ligament (ACL) graft failure, and may lead to chronic instability (1,5,8,11,12). Therefore, it would be desirable to predict posterolateral instability as early as possible not only by clinical testing but also by imaging.

MRI studies (13,14) reveal that injuries of PLC structures occur more frequently than expected by clinical examination and radiographs, and may manifest in up to 20% of patients with an ACL tear. It remains unclear which MRI findings indicate posterolateral instability in patients with acute ACL tear, and which do not. Furthermore, not all PLC structures are consistently viewed on MR images (3,10).

The aims of our study were to determine the diagnostic performance of various MRI findings for helping to predict posterolateral instability in patients with acute complete ACL tears and to identify the most significant MRI predictors of posterolateral instability by performing a decision tree analysis. Our hypothesis was that we could correctly predict posterolateral instability in a high number of patients on the basis of decision tree analysis of MRI findings.

Materials and Methods

Study Population

Our retrospective cohort study was approved by the local ethics committee (Cantonal Ethics Committee, Zurich, Switzerland), and informed consent was waived by the institutional review board. Our clinical database (Kisim version 4.964; Cistec, Zurich, Switzerland) was searched for a consecutive series of patients who underwent ACL reconstruction with or without concomitant PLC reconstruction (modified Larson procedure

Abbreviations

ACL = anterior cruciate ligament, PLC = posterolateral corner

Summary

Complete tear or fibular avulsion of the lateral collateral ligament was the most significant predictor at MRI of posterolateral instability in patients with acute anterior cruciate ligament tears.

Implications for Patient Care

- Complete tear or fibular avulsion of the lateral collateral ligament was the most significant predictor at MRI of posterolateral instability in patients with acute anterior cruciate ligament tear.
- The assessment of smaller posterolateral corner structures (popliteofibular ligament, fabellofibular ligament, and popliteomeniscal fascicles) did not improve diagnostic performance of current MRI to help predict posterolateral instability.

[15,16]) at our institution between June 2014 and February 2017. Inclusion criteria were as follows: age, 18 years or older; available MRI study of the knee performed within 10 days after trauma; no documented history of previous ipsilateral knee trauma or surgery; and no documented subsequent new trauma of the knee between MRI and knee reconstruction surgery. Exclusion criteria were incomplete MRI dataset (sequences not available in all three standard planes) or insufficient image quality.

Clinical Assessment

The decision to reconstruct the PLC was on the basis of preoperative clinical assessment with the so-called dial test (performed by S.F.F., with 15 years of dedicated experience in knee surgery). The dial test is, to our knowledge, the most widely used clinical test for posterolateral rotational instability (5,8,9) and is included in the standard clinical examination of the knee at our institution. It is performed as follows: at 30° of knee flexion, increased external tibial rotation of 10° compared with the contralateral side indicates PLC injury. This test was performed during the preoperative exploration in all patients while they underwent anesthesia.

MRI

All patients who underwent imaging at our institution had undergone MRI at 3.0 T (Magnetom Skyra Fit; Siemens Healthcare, Erlangen, Germany) or 1.5 T (Magnetom Avanto Fit; Siemens Healthcare). In patients who had undergone MRI at other institutions, the external MRI datasets were used for the analysis (Table 1). The images were acquired at 1.5 or 3.0 T, and imaging protocols included at least four sequences at three standard imaging planes (axial, coronal, and sagittal) with at least one T1-weighted and one fluid-sensitive sequence (proton-density weighted or T2 weighted with fat suppression, and/or short inversion time inversion recovery).

Image Analysis

MR images were evaluated by two independent musculoskeletal radiologists blinded to clinical data (A.B.R. and L.F., with 11 and 5 years of experience in musculoskeletal radiology, respectively). The readers were not blinded to the type of MRI sequence (eg, T2 weighted or proton density weighted). Different structures of the knee were assessed as follows:

1. Lateral collateral ligament, medial collateral ligament, posterior cruciate ligament, popliteus tendon, and biceps femoris tendon: normal, strain/partial tear (indicated by partial discontinuation of fiber structure, accompanying soft tissue edema and bleeding), complete tear (complete fiber discontinuation, with or without waviness of the remaining ligament), or osseous avulsion (visible bone fragment attached to ligament or tendon, with or without displacement).
2. Popliteofibular ligament and fabellofibular ligament: visibility at any imaging plane (axial, coronal, sagittal) (yes or no), presence or absence of edema if visible.
3. Posterosuperior and anteroinferior popliteomeniscal fascicles: visibility in the sagittal plane (yes or no).
4. Fat pad located between the popliteus tendon, the biceps femoris tendon, and the lateral head of the gastrocnemius, surrounding the lateral inferior genicular artery: presence or absence of fluid signal intensity (further referred to as posterolateral fat pad edema), either edema or frank fluid collection, depicted at any imaging plane (axial, coronal, sagittal).
5. Bones: presence or absence of bone marrow edema in the medial and lateral femoral condyle and tibial plateau visible at any imaging plane (indicated by high signal intensity at fluid-sensitive sequences, ie, fat-suppressed proton-density-weighted, T2-weighted, or short inversion time inversion recovery sequences); manifestation of cortical compression fractures of the lateral femoral condyle and tibial plateau, and presence of a Segond fracture, each indicated by cortical discontinuity and/or impression of 1 mm or greater, visible at at least one imaging plane.
6. Medial and lateral meniscus: presence or absence of meniscal tears (visible linear high signal intensity at fluid-sensitive sequences on at least two adjacent sections and/or at two different imaging planes).

Statistical Analysis

Statistical analysis was performed by using commercially available software (SPSS version 23; IBM, Somers, NY). The interobserver agreement was investigated by calculating Cohen κ coefficient and interpreted according to Landis and Koch (κ ≤ 0.20, slight; 0.21–0.40, fair; 0.41–0.60, moderate; 0.61–0.80, substantial; and ≥0.81, almost perfect) (17).

Parameters were compared between patients who underwent isolated ACL reconstruction (referred to as the ACL-only group) and those with additional PLC reconstruction (referred to as the ACL with PLC group). Sensitivity, specificity, positive likelihood ratio, and negative likelihood ratio were calculated for each parameter. Clinical evidence of posterolateral instability requiring surgical PLC reconstruction served as reference standard. The diagnostic accuracy of MRI parameters was determined by calculating respective areas under the curve. For discrimination between the two study groups, an area under the curve of

Table 1: Detailed MRI Protocol

	1.5-T Imager				3.0-T Imager			
Parameter	Coronal STIR	Coronal T1 Weighted	Sagittal PD Dixon	Axial PDfs	Coronal STIR	Coronal T1 Weighted	Sagittal PD Dixon	Axial PDfs
TR/TE (msec)	4000/39	613/14	3190/27	3840/31	4460/34	700/9.4	3780/39	4350/40
ETL	8	3	7	8	12	2	10	7
NSA	1	2	1	1	1	1	1	1
Section thickness (mm)	3	3	3	2.5	3	3	3	2.5
Spacing (mm)	3.6	3.6	3.6	3	3.3	3.3	3.6	2.75
Matrix	288 × 384	336 × 448	325 × 448	314 × 448	307 × 384	358 × 448	358 × 448	307 × 384
FOV (mm^2)	170 × 170	170 × 170	163 × 180	160 × 160	159 × 159	160 × 160	159 × 159	150 × 150
TA (min:sec)	3:32	1:22	4:50	3:04	3:11	1:38	4:43	2:58

Note.—ETL = echo train length, FOV = field of view, PD = proton-density weighted, PDfs = PD with fat saturation, STIR = short inversion time inversion recovery, TR = repetition time, TE = echo time, NSA = number of signals acquired, TA = acquisition time.

0.80–0.89 was considered to indicate a good test; 0.70–0.79, a fair test; and 0.51–0.69, a poor test (18). To test for differences between the groups, continuous variables were compared by using the two-sample Student *t* test and binomial variables were compared by using Fisher exact test (two-sided). Power analysis (G*power software, version 3.1.9.2; Heinrich Heine University, Dusseldorf, Germany) (19) with predefined power (power level, 0.80) and given sample size (19 + 143) revealed a required *P* value of less than .001 to indicate statistically significant differences.

On the basis of all evaluated parameters, decision tree analysis with the χ^2 calculation was used to determine the most significant MRI predictors of posterolateral instability. For this analysis, the χ^2 automatic interaction detection algorithm was applied (20).

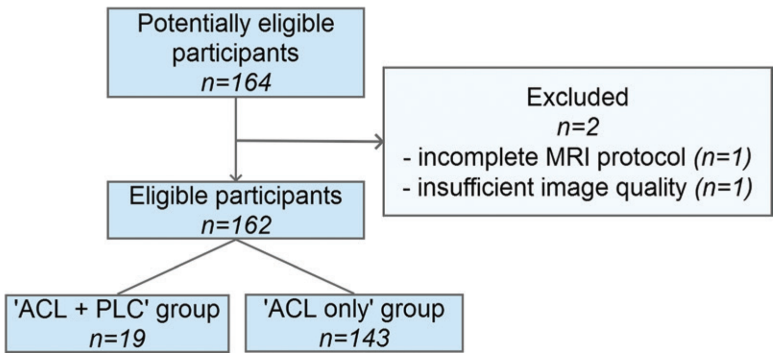


Figure 1: Flowchart of patient inclusion and exclusion. ACL = anterior cruciate ligament, ACL only = patient group who underwent isolated ACL reconstruction, ACL + PLC = patient group with additional PLC reconstruction, PLC = posterolateral corner.

Results

Study Population

We identified 164 patients by using the database search. Two patients who were imaged at other institutions were excluded because of incomplete MRI protocol (missing sequence in the axial plane; *n* = 1) and insufficient image quality (substantial motion artifacts throughout all sequences; *n* = 1). Of the remaining patients, 54 of 162 (33.3%) had been imaged at our institution. The patients were divided into groups of those who had undergone isolated ACL reconstruction (ACL-only group, *n* = 143) and those with additional PLC reconstruction (ACL with PLC group, *n* = 19) (Fig 1). Three patients (from the ACL with PLC group) had undergone additional open medial and/or posteromedial reconstruction. Detailed demographic data for the two groups is in Table 2.

Examples of PLC injuries on different imaging planes are in Figures 2–4. Normal anatomy is explained in detail in Figures E1–E3 (online).

Interobserver Agreement

The interobserver agreement was perfect for Segond fractures (κ = 1.0), good for cortical compression fractures (femoral condyle, κ = 0.89; tibial plateau, κ = 0.80), substantial for medial and lateral meniscal tear (κ = 0.77 and 0.66, respectively), and substantial to almost perfect for bone marrow edema (medial femoral condyle, κ = 0.69; medial tibial plateau, κ = 0.73; lateral femoral condyle, κ = 0.86; and lateral tibial plateau, κ = 0.79). Moderate agreement was found for the lateral collateral ligament (κ = 0.53), medial collateral ligament (κ = 0.56), popliteus tendon (κ = 0.56), biceps femoris tendon (κ = 0.58), posterior cruciate ligament (κ = 0.54), and posterolateral fat pad edema (κ = 0.52). The agreement was fair for the popliteofibular ligament (κ = 0.26) and fabellofibular ligament (κ = 0.40), and slight concerning the posterosuperior and anteroinferior popliteomeniscal fascicles (κ = 0.17 and 0.14, respectively).

Frequency, Diagnostic Performance, and Statistical Significance of Different Findings

The frequency, diagnostic performance, and statistical significance of different findings are listed in detail in Tables 3 and 4.

Various findings demonstrated a high specificity but low sensitivity for clinically observed posterolateral instability.

Table 2: Demographic Data of the Two Study Groups

Parameter	Both Groups (n = 162)	ACL with PLC (n = 19)	ACL Only (n = 143)	P Value
Mean age (y)	32.8 ± 10.0 (18–58)	29.7 ± 11.7 (18–58)	33.2 ± 9.7 (19–57)	.15
Sex				.46
No. of men	95	13	82	
No. of women	67	6	61	
No. of examinations per side				.05
Left	85	14	71	
Right	77	5	72	
Mean interval between trauma and MRI (d)	3.9 ± 2.9 (0–10)	3.1 ± 2.4 (0–9)	4.0 ± 3.0 (0–10)	.21
Mean interval between MRI and surgery (d)	39.1 ± 44.1 (0–273)	46.1 ± 74.6 (1–273)	38.2 ± 38.6 (0–187)	.46
No. of MRIs performed at the author's institution*	54 (33.3)	5 (26.3)	49 (34.3)	.61
Magnetic field strength (no. of examinations)*				.21
1.5 T	132 (71.5)	16	116	
3.0 T	30 (18.5)	3	27	

Note.—Unless otherwise indicated, data are ± standard deviation and data in parentheses are range. Patients who underwent isolated ACL reconstruction (referred to as the ACL-only group) and those with additional PLC reconstruction (referred to as the ACL with PLC group). ACL = anterior cruciate ligament, PLC = posterolateral corner.

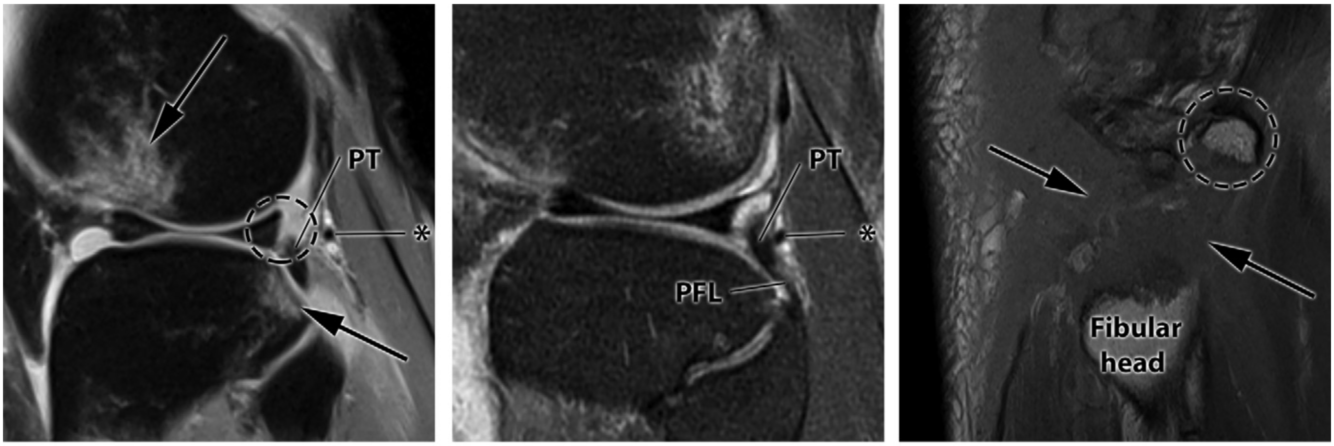
* Data in parentheses are percentages.

a. b. c.

Figure 2: Posterolateral corner injuries of the right knee at the coronal plane. **(a)** Coronal short inversion time inversion recovery image in a 49-year-old female patient from the anterior cruciate ligament (ACL)–only group (ie, ACL rupture without clinical evidence of posterolateral instability) 1 day after trauma; there is high signal intensity in the popliteofibular ligament (PFL). The lateral inferior genicular artery (*) is lateral to the PFL. The biceps femoris tendon (BT) is intact. Bone marrow edema is depicted on the posterolateral tibial plateau (arrow). **(b)** Coronal short inversion time inversion recovery image in a 38-year-old male patient from the patient group with additional posterolateral corner (PLC) reconstruction (referred to as the ACL with PLC group; ACL rupture with clinical evidence of posterolateral instability) 5 days after trauma with avulsion fracture of the fibular head (dashed circle) by the lateral collateral ligament (LCL) and BT. The popliteus tendon (PT) is torn at its femoral attachment. There is marked soft tissue edema in the posterolateral corner. **(c)** Coronal short inversion time inversion recovery image in an 18-year-old male patient from the ACL with PLC group 4 days after trauma. The LCL and PT are torn close to their femoral attachment. The BT is torn at its distal musculotendinous junction. No bone marrow edema is manifest in the lateral femoral condyle and lateral tibial plateau.

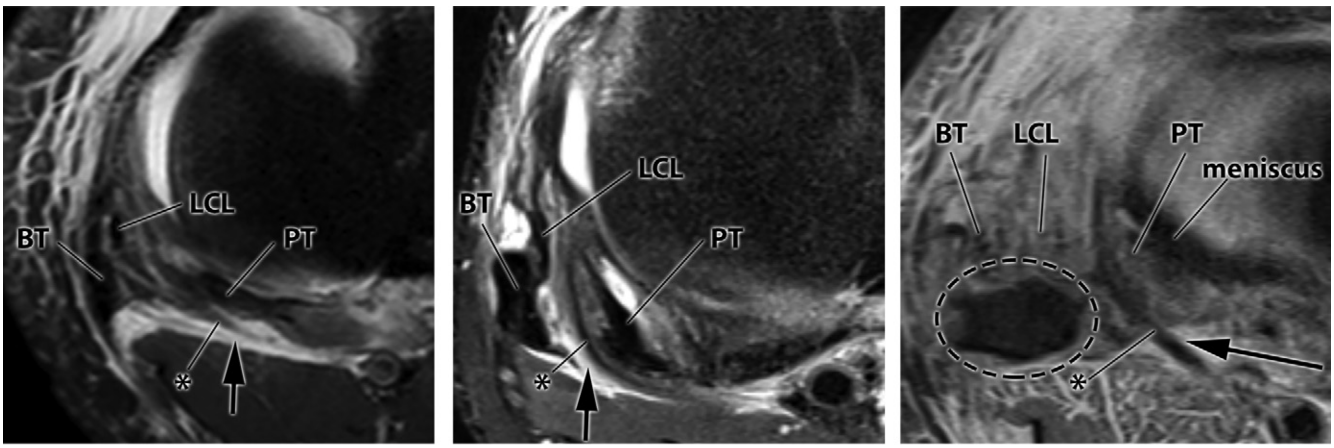
These findings included complete tear or avulsion of the lateral collateral ligament (specificity and sensitivity for readers 1 and 2, respectively: 95.1% and 52.6%, and 97.9% and 57.9%), posterior cruciate ligament (specificity and sensitivity for readers 1 and 2, respectively: 96.5% and 10.5%, and 96.5% and 10.5%), popliteus tendon (specificity and sensitivity for readers 1 and 2, respectively: 100% and 15.8%, and 98.6% and 21.1%), and biceps femoris tendon (specificity and sensitivity for readers 1 and 2, respectively: 100% and 21.1%, and 100% and 26.3%). Strains or partial tears of most of these structures were neither highly specific nor highly sensitive. Complete tear or fibular avulsion of the lateral collateral ligament was the only parameter with an area under the curve greater than 0.70 for both readers (reader 1 vs reader 2 area under the curve, 0.75 vs 0.80, respectively), which indicated a fair test. No femoral avulsions of the lateral collateral ligament occurred in our study population. Receiver operating characteristic curves for significant findings are shown in Figure 5.

The smaller structures of the PLC were not consistently identified. The popliteofibular ligament was depicted in 86 of 162 patients (53.1%) by reader 1 and in 102 of 162 patients (63.0%) by reader 2. It was more



a. b. c.

Figure 3: Posterolateral corner injuries at the sagittal plane. **(a)** Sagittal fat-saturated proton density-weighted image in a 50-year-old female patient from the anterior cruciate ligament (ACL)–only group (ie, ACL rupture without clinical evidence of posterolateral instability) 1 day after trauma. No popliteomeniscal fascicles are visible (dashed circle shows the popliteal hiatus). The partially displayed popliteus tendon (PT) shows a normal course. The lateral inferior genicular artery (*) is accompanied by small veins (hyperintense round structures proximal) and surrounded by fluid. Bone marrow edema (arrows) is manifest in the anterior aspect of the lateral femoral condyle and in the posterolateral tibial plateau. **(b)** Sagittal short inversion time inversion recovery image in a 58-year-old male patient from the patient group with additional posterolateral corner (PLC) reconstruction (referred to as the ACL with PLC group; ACL rupture with clinical evidence of posterolateral instability) 2 days after trauma. There is minimal fluid in the soft tissues distal to the lateral inferior genicular artery (*). The popliteomeniscal fascicles, popliteus tendon (PT), and popliteofibular ligament (PFL) are intact. Bone marrow edema is manifest in the posterior part of the lateral femoral condyle. **(c)** Sagittal proton density–weighted image in a 38-year-old male patient from the ACL with PLC group 5 days after trauma. Extensive soft tissue hematoma (arrows) is manifest between the avulsion fragment (dashed circle) and the fibular head.



a. b. c.

Figure 4: Posterolateral corner injuries in the right knee at the axial plane. **(a)** Axial fat-saturated proton density-weighted image in an 18-year-old female patient from the patient group with additional posterolateral corner (PLC) reconstruction (referred to as the anterior cruciate ligament [ACL] with PLC group; ACL rupture with clinical evidence of posterolateral instability) 7 days after trauma. There is posterolateral fat pad edema (hyperintense signal intensity, arrow) around the lateral inferior genicular artery (*). The popliteus tendon (PT) is intact. The biceps femoris tendon (BT) and lateral collateral ligament (LCL) show a normal course. **(b)** Axial fat-saturated proton density-weighted image in a 25-year-old male patient from the ACL-only group (ie, ACL rupture without clinical evidence of posterolateral instability) 2 days after trauma. The lateral inferior genicular artery (*) shows a boomerang-shaped course posterolateral to the PT. Again, posterolateral fat pad edema is manifest (arrow), which reflects the low specificity of this finding for posterolateral knee instability. The PT, LCL, and BT are intact. **(c)** Axial fat-saturated proton density-weighted image in a 38-year-old male patient from the ACL with PLC group 5 days after trauma. The LCL, the BT, and the PT are completely torn and diffusely swollen. There is a displaced fragment of the fibular head (dashed circle). A large amount of fluid is depicted in the posterolateral fat pad (arrow) and in the subcutaneous tissue. The lateral inferior genicular artery remains visible as an anatomic landmark (*).

often rated edematous in the ACL with PLC group; however, this finding was statistically significant only for reader 2. A posterosuperior popliteomeniscal fascicle was found in 115 of 162 patients (71.0%) by reader 1 and in 104 of 162 patients (64.2%) by reader 2, whereas an anteroinferior fascicle was observed in 109 of 162 patients (67.3%) by reader 1 and in 96 of 162 patients (59.3%) by reader 2. Both readers identified a fabellofibular ligament in 13 of 162 patients (8.0%).

No differences between the groups were found regarding the occurrence of posterolateral fat pad edema, and medial and lateral meniscal tears (P values: reader 1, .53, $>$.99 and .56, respectively; reader 2, .21, .21, and .77, respectively).

Table 3: Frequency, Diagnostic Performance, and Statistical Significance of Different Findings in Both Study Groups: Reader 1

Parameter	ACL with PLC Group (n = 19)	ACL-Only Group (n = 143)	Sensitivity (%)	Specificity (%)	Positive Likelihood Ratio	Negative Likelihood Ratio	AUC (95% CI)	P Value*
LCL								
Strain/partial tear	7	98	36.8 (16.3, 61.6)	31.5 (24.0, 39.8)	0.5 (0.3, 1.0)	2.0 (1.3, 3.1)	0.66 (0.52, 0.79)	<.05
Complete tear or avulsion	10	7	52.6 (28.9, 75.6)	95.1 (90.2, 98.0)	10.8 (4.7, 24.9)	0.5 (0.3, 0.8)	0.75 (0.61, 0.90)	<.001
MCL								
Strain/partial tear	11	78	57.9 (33.5, 79.8)	45.5 (37.1, 54.0)	1.1 (0.7, 1.6)	0.9 (0.5, 1.6)	0.52 (0.38, 0.66)	.81
Complete tear or avulsion	3	32	15.8 (3.4, 39.6)	77.6 (69.9, 84.2)	0.7 (0.2, 2.1)	1.1 (0.9, 1.3)	0.56 (0.43, 0.69)	.77
Posterior cruciate ligament								
Strain/partial tear	9	20	47.4 (23.4, 71.1)	86.0 (79.2, 91.2)	3.4 (1.8, 6.3)	0.6 (0.4, 0.9)	0.67 (0.52, 0.81)	<.01
Complete tear or avulsion	2	5	10.5 (1.3, 33.1)	96.5 (92.0, 98.9)	3.0 (0.6, 14.5)	0.9 (0.8, 1.1)	0.51 (0.37, 0.65)	.19
PT								
Strain/partial tear	13	102	68.4 (43.5, 87.4)	28.7 (21.4, 36.8)	1.0 (0.7, 1.3)	1.1 (0.5, 2.2)	0.51 (0.37, 0.65)	.80
Complete tear or avulsion	3	0	15.8 (3.4, 39.6)	100 (97.5, 100)	…	0.8 (0.7, 1.0)	0.58 (0.43, 0.74)	<.01
BT								
Strain/partial tear	11	71	57.9 (33.5, 79.8)	50.3 (41.9, 58.8)	1.2 (0.8, 1.8)	0.8 (0.5, 1.5)	0.54 (0.40, 0.68)	.63
Complete tear or avulsion	4	0	21.1 (6.1, 45.6)	100 (97.5, 100)	…	0.8 (0.6, 1.0)	0.61 (0.45, 0.77)	<.001
PFL								
Nonvisibility	10	64	52.6 (28.9, 75.6)	55.2 (46.7, 63.6)	1.2 (0.7, 1.9)	0.9 (0.5, 1.4)	0.50 (0.30, 0.70)	.63
Edematous when visible	9	56	100 (66.4, 100)	29.1 (19.4, 40.4)	1.4 (1.2, 1.6)	0	0.89 (0.79, 0.99)	.10
FFL								
Nonvisibility	16	133	84.2 (60.4, 96.6)	7.0 (3.4, 12.5)	0.9 (0.7, 1.1)	2.3 (0.7, 7.5)	0.52 (0.32, 0.73)	.18
Edematous when visible	1	2	33.3 (0.8, 90.6)	80.0 (44.4, 97.5)	1.7 (0.2, 12.6)	0.8 (0.4, 2.0)	0.54 (0.00, 1.00)	>.99
Posterosuperior popliteomeniscal fascicle								
Nonvisibility	5	42	26.3 (9.2, 51.2)	70.6 (62.4, 77.9)	0.9 (0.4, 2.0)	1.0 (0.8, 1.4)	0.58 (0.40, 0.76)	>.99
Anteroinferior popliteomeniscal fascicle								
Nonvisibility	7	46	36.8 (16.3, 61.6)	67.8 (59.5, 75.4)	1.2 (0.6, 2.2)	0.9 (0.7, 1.3)	0.54 (0.35, 0.73)	.80
Posterolateral fat pad edema	16	112	84.2 (60.4, 96.6)	21.7 (15.2, 29.3)	1.1 (0.9, 1.3)	0.7 (0.3, 2.2)	0.55 (0.41, 0.68)	.53
Medial meniscus								
Tear	6	50	31.6 (12.6, 56.6)	65.0 (56.6, 72.8)	0.9 (0.5, 1.8)	1.1 (0.8, 1.5)	0.53 (0.40, 0.67)	>.99
Lateral meniscus								
Tear	5	30	26.3 (9.2, 51.2)	79.0 (71.4, 85.4)	1.3 (0.6, 2.8)	0.9 (0.7, 1.2)	0.54 (0.39, 0.68)	.56
Bone marrow edema								
Medial femoral condyle	12	57	63.2 (38.4, 83.7)	60.1 (51.6, 68.2)	1.6 (1.1, 2.4)	0.6 (0.3, 1.1)	0.64 (0.50, 0.77)	.08
Medial tibial plateau	15	83	79.0 (54.4, 94.0)	42.0 (33.8, 50.5)	1.4 (1.0, 1.8)	0.5 (0.2, 1.2)	0.60 (0.47, 0.73)	.09
Lateral femoral condyle	13	97	68.4 (43.5, 87.4)	32.2 (24.6, 40.5)	1.0 (0.7, 1.4)	1.0 (0.5, 2.0)	0.51 (0.36, 0.67)	>.99
Lateral tibial plateau	13	134	68.4 (43.5, 87.4)	6.3 (2.9, 11.6)	0.7 (0.5, 1.0)	5.0 (2.0, 12.5)	0.63 (0.48, 0.79)	<.05

Table 3 *(continues)*

Table 3 (*continued*): Frequency, Diagnostic Performance, and Statistical Significance of Different Findings in Both Study Groups: Reader 1

Parameter	ACL with PLC Group (n = 19)	ACL-only Group (n = 143)	Sensitivity (%)	Specificity (%)	Positive Likelihood Ratio	Negative likelihood Ratio	AUC (95% CI)	P Value*
Cortical compression fracture								
Lateral femoral condyle	7	17	36.8 (16.3, 61.6)	88.1 (81.7, 92.9)	3.1 (1.5, 6.5)	0.7 (0.5, 1.0)	0.62 (0.48, 0.77)	.01
Lateral tibial plateau	3	30	15.8 (3.4, 39.6)	79.0 (71.4, 85.4)	0.8 (0.3, 2.2)	1.1 (0.9, 1.3)	0.52 (0.39, 0.66)	.43
Segond fracture	2	1	10.5 (1.3, 33.1)	99.3 (96.2, 99.9)	15.1 (1.4, 158.2)	0.9 (0.8, 1.1)	0.55 (0.40, 0.70	<.05

Note.—Data in parentheses are 95% confidence intervals. P values less than .001 indicate statistically significant differences. ACL = anterior cruciate ligament, AUC = area under the curve, BT = biceps tendon, CI = confidence interval, LCL = lateral collateral ligament, FFL = fabellofibular ligament, MCL = medial collateral ligament, PFL = patellofibular ligament, PLC = posterolateral corner, PT = popliteus tendon.

* P values found by two-sided Fisher exact test.

Bone marrow edema in the lateral tibial plateau was common in both groups but less frequent in the ACL with PLC group compared with the ACL-only group (reader 1, $P < .05$; reader 2, $P < .01$). However, bone marrow edema was more frequent in the medial femoral condyle in the ACL with PLC group (reader 1, $P = .08$; reader 2, $P < .05$). A Segond fracture was observed in two patients who were in the ACL with PLC group and in one patient who was in the ACL-only group.

Decision Tree Analysis

Decision tree analysis revealed that a complete tear or fibular avulsion of the lateral collateral ligament was the most statistically significant finding to help predict posterolateral instability (Fig 6). When this finding was absent, a second branch of the decision tree concerning biceps femoris tendon injury slightly optimized the dichotomization between both groups for reader 1 because a complete tear or fibular avulsion of the biceps femoris tendon (in the absence of complete tear or avulsion of the lateral collateral ligament) was found in only one patient who was in the ACL with PLC group. This second branch was not required for the data from reader 2. With these decision trees, patients were correctly assigned to their groups in 147 of 162 instances (90.7%) by reader 1 and in 151 of 162 instances (93.2%) by reader 2.

Discussion

PLC injury most commonly occurs with varus stress, especially in a hyperextended knee (3,8). Three structures are considered essential for posterolateral stability: the lateral collateral ligament, popliteus tendon, and popliteofibular ligament (8,11,12). The lateral collateral ligament is the major stabilizer against varus stress. The popliteus tendon and popliteofibular ligament both stabilize against external rotation, and, if the lateral collateral ligament is torn, act as secondary stabilizers against varus stress (8,21,22). In case of ACL rupture, the PLC structures also stabilize against anterior translation and internal rotation (5,8,23).

A good clinical examination makes the diagnosis of posterolateral instability possible in most patients (8). Although clinical examination remains the reference standard, it would be desirable to be able to predict posterolateral instability at MRI because it may be difficult to observe in the setting of acute trauma.

In an MRI study, Temponi et al (13) detected signs of PLC injury in 20% of patients with acute ACL tear, with frequent involvement of small structures such as the popliteomeniscal fascicles observed at MRI, but the authors did not correlate these findings with clinical instability. Ahn et al (24) reported frequent thickening of the popliteofibular ligament, the fabellofibular ligament, and the popliteomeniscal fascicles in patients with PLC instability; however, they were only compared with healthy control participants. In addition, these small structures are not always observed at MRI (popliteofibular ligament visible in 8%–90% of patients; fabellofibular ligament visible in 33%–48% of patients; popliteomeniscal fascicles visible in 60%–94% of patients) (1,3,7,10,22,25), which was confirmed by the results of our study. Their interindividual variability in size and

Table 4: Frequency, Diagnostic Performance, and Statistical Significance of Different Findings in Both Study Groups: Reader 2

Parameter	ACL with PLC Group (n = 19)	ACL-Only Group (n = 143)	Sensitivity (%)	Specificity (%)	Positive Likelihood Ratio (95% CI)	Negative Likelihood Ratio (95% CI)	AUC (95% CI)	P Value*
LCL								
Strain/partial tear	4	80	21.1 (6.1, 45.6)	44.1 (35.8, 52.6)	0.4 (0.2, 0.9)	1.8 (1.3, 2.4)	0.67 (0.55, 0.79)	<.01
Complete tear or avulsion	11	3	57.9 (33.5, 79.8)	97.9 (94.0, 99.6)	27.6 (8.5, 90.1)	0.4 (0.3, 0.7)	0.80 (0.65, 0.94)	<.001
MCL								
Strain/partial tear	11	61	57.9 (33.5, 79.8)	57.3 (48.8, 65.6)	1.4 (0.9, 2.1)	0.7 (0.4, 1.3)	0.58 (0.47, 0.77)	.23
Complete tear or avulsion	3	18	15.8 (3.4, 39.6)	87.4 (80.8, 92.4)	1.3 (0.4, 3.9)	1.0 (0.8, 1.2)	0.51 (0.37, 0.65)	.72
Posterior cruciate ligament								
Strain/partial tear	6	12	31.6 (12.6, 56.6)	91.6 (85.8, 95.6)	3.8 (1.6, 8.9)	0.8 (0.6, 1.0)	0.62 (0.47, 0.77)	<.01
Complete tear or avulsion	2	5	10.5 (1.3, 33.1)	96.5 (92.0, 98.9)	3.0 (0.6, 14.5)	0.9 (0.8, 1.1)	0.54 (0.39, 0.69)	.19
PT								
Strain/partial tear	10	57	52.6 (28.9, 75.6)	60.1 (51.6, 67.2)	1.3 (0.8, 2.1)	0.8 (0.5, 1.3)	0.56 (0.43, 0.70)	.33
Complete tear or avulsion	4	2	21.1 (6.1, 45.6)	98.6 (95.0, 99.8)	15.1 (3.0, 76.7)	0.8 (0.6, 1.0)	0.60 (0.45, 0.76)	<.01
BT								
Strain/partial tear	7	40	36.8 (16.3, 61.6)	72.0 (63.9, 79.2)	1.3 (0.7, 2.5)	0.9 (0.6, 1.3)	0.54 (0.40, 0.69)	.43
Complete tear or avulsion	5	0	26.3 (9.2, 51.2)	100 (97.5, 100)	…	0.7 (0.6, 1.0)	0.64 (0.48, 0.80)	<.001
PFL								
Nonvisibility	7	53	36.8 (16.3, 61.6)	62.9 (54.4, 70.9)	1.0 (0.5, 1.9)	1.0 (0.7, 1.5)	0.59 (0.38, 0.79)	>.99
Edematous when visible	11	19	91.7 (61.5, 99.8)	78.9 (69.0, 86.8)	4.3 (2.8, 6.7)	0.1 (0.0, 0.7)	0.65 (0.49, 0.80)	<.001
FFL								
Nonvisibility	18	131	94.7 (74.0, 99.9)	8.4 (4.4, 14.2)	1.0 (0.9, 1.2)	0.6 (0.1, 4.6)	0.53 (0.34, 0.72)	>.99
Edematous when visible	0	1	0 (0, 97.5)	92.3 (64.0, 99.8).	0	1.1 (0.9, 1.3)	0.57 (0.17, 0.96)	>.99
posterosuperior popliteomeniscal fascicle								
Nonvisibility	8	50	42.1 (20.3, 66.5)	65.0 (56.6, 72.8)	1.2 (0.7, 2.1)	0.9 (0.6, 1.3)	0.50 (0.30, 0.70)	.61
Anteroinferior popliteomeniscal fascicle								
Nonvisibility	10	56	52.6 (28.9, 75.6)	60.8 (52.3, 68.9)	1.3 (0.8, 2.2)	0.8 (0.5, 1.3)	0.54 (0.34, 0.74)	.32
Posterolateral fat pad edema	15	91	79.0 (54.4, 94.0)	36.4 (28.5, 44.8)	1.2 (1.0, 1.6)	0.6 (0.2, 1.4)	0.57 (0.43, 0.70)	.21
Medial meniscus								
Tear	4	53	21.1 (6.1, 45.6)	62.9 (54.5, 70.9)	0.6 (0.2, 1.4)	1.3 (1.0, 1.6)	0.57 (0.44, 0.71)	.21
Lateral meniscus								
Tear	5	31	26.3 (9.2, 51.2)	78.3 (70.7, 84.8)	1.2 (0.5, 2.7)	0.9 (0.7, 1.3)	0.53 (0.39, 0.68)	.77
Bone marrow edema								
Medial femoral condyle	12	51	63.2 (38.4, 83.7)	64.3 (55.9, 72.2)	1.8 (1.2, 2.7)	0.6 (0.3, 1.0)	0.66 (0.52, 0.79)	<.05
Medial tibial plateau	12	70	63.2 (38.4, 83.7)	51.0 (42.6, 59.5)	1.3 (0.9, 1.9)	0.7 (0.4, 1.3)	0.56 (0.42, 0.70)	.33
Lateral femoral condyle	11	93	57.9 (33.5, 79.8)	35.0 (27.2, 43.4)	0.9 (0.6, 1.3)	1.2 (0.7, 2.1)	0.54 (0.40, 0.69)	.61
Lateral tibial plateau	12	133	63.2 (38.4, 83.7)	7.0 (3.4, 12.5)	0.7 (0.5, 1.0)	5.3 (2.3, 12.2)	0.66 (0.51, 0.81)	<.01

Table 4 *(continues)*

Table 4 (*continued*): Frequency, Diagnostic Performance, and Statistical Significance of Different Findings in Both Study Groups: Reader 2

Parameter	ACL with PLC Group (n = 19)	ACL-Only Group (n = 143)	Sensitivity (%)	Specificity (%)	Positive Likelihood Ratio (95% CI)	Negative Likelihood Ratio (95% CI)	AUC (95% CI)	P Value*
Cortical compression fracture								
Lateral femoral condyle	6	18	31.6 (12.6, 56.6)	87.4 (80.8, 92.4)	2.5 (1.1, 5.5)	0.8 (0.6, 1.1)	0.60 (0.45, 0.74)	.04
Lateral tibial plateau	6	39	31.6 (12.6, 56.6)	72.7 (64.7, 79.8)	1.2 (0.6, 2.4)	0.9 (0.7, 1.3)	0.52 (0.38, 0.67)	.44
Segond fracture	2	1	10.5 (1.3, 33.1)	99.3 (96.2, 99.9)	15.1 (1.4, 158.2)	0.9 (0.8, 1.1)	0.55 (0.40, 0.70	<.05

Note.—Data in parentheses are 95% confidence intervals. P values less than .001 indicate statistically significant differences. ACL = anterior cruciate ligament, BT = biceps tendon, AUC = area under the curve, CI = confidence interval, LCL = lateral collateral ligament, FFL = fabellofibular ligament, MCL = medial collateral ligament, PFL = patellofibular ligament, PLC = posterolateral corner, PT = popliteus tendon.

* P values found by two-sided Fisher exact test.

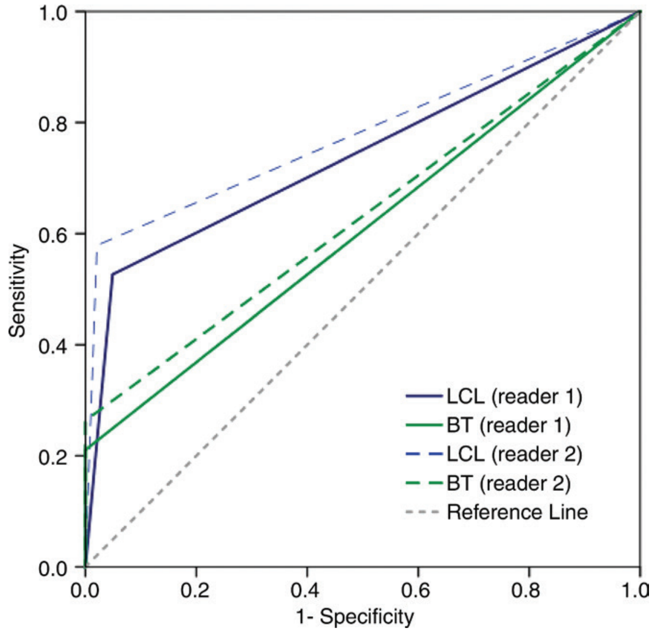


Figure 5: Receiver operating characteristic curves of complete lateral collateral ligament (LCL) and biceps femoris tendon (BT) tears as measured by reader 1 and reader 2 for discrimination between patients who underwent reconstruction of the anterior cruciate ligament alone or with posterolateral corner reconstruction.

visibility seems too high and the interobserver agreement for these structures too insufficient to use their thickness as a reliable sign of PLC injury. Even with our simple assessment on the basis of visibility (vs a three-point grading system used in other studies [26]), interobserver agreement was only fair. The ability to view small structures such as the popliteofibular ligament may be improved with the acquisition of oblique coronal sections (27) or isotropic three-dimensional sequences (28). Because of imaging time restrictions, however, these sequences are not acquired at many institutions. Three-dimensional imaging may replace two-dimensional imaging in the near future because of new acceleration techniques (29).

The manifestation of posterolateral fat pad edema may be an imaging surrogate marker indicating injury of the popliteofibular ligament (3,22) but it was not a specific sign of posterolateral instability in our study. A helpful anatomic landmark to identify the smaller PLC structures is the lateral inferior genicular artery, which courses between the popliteofibular ligament and the fabellofibular ligament (30). The popliteofibular ligament is directly anteromedial to this artery, whereas the fabellofibular ligament lies directly posterolateral to it (Figs E1–E2 [online]).

The term *arcuate ligament* caused confusion in the past because of its inconsistent use, and its existence is controversial: some authors have used it to describe the fabellofibular ligament, popliteofibular ligament, popliteal aponeurosis to the lateral meniscus, or capsular arm of the short head of the biceps femoris tendon, whereas others describe it as a thickening of the posterolateral joint capsule rather than a distinct structure (5,9,31,32). Those authors who describe it as a separate structure state that it is difficult view at MRI, and that it is not constantly viewable (7,31). In accordance to recent

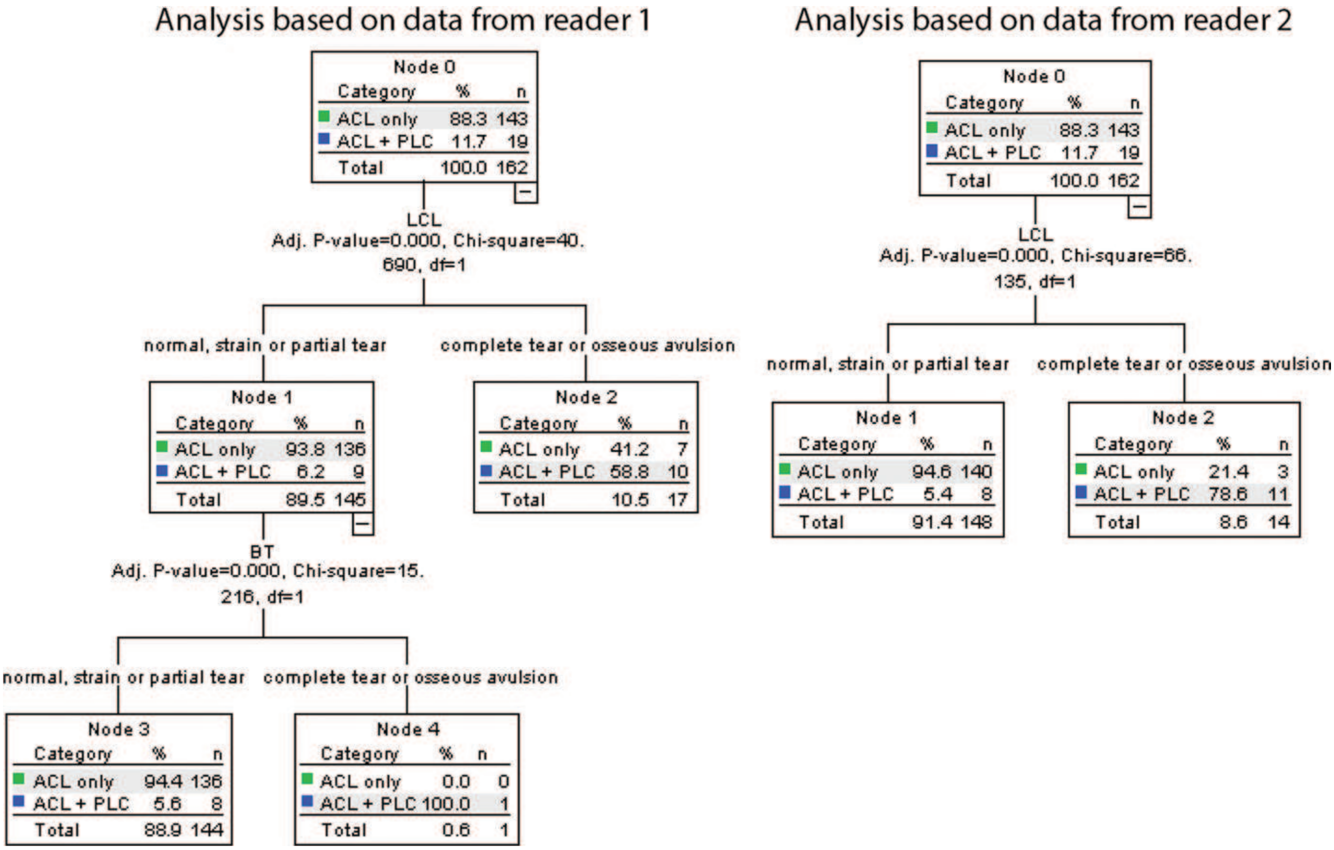


Figure 6: Decision tree analysis. Decision tree analysis revealed that a complete tear or avulsion of the lateral collateral ligament was the most significant predictor of posterolateral instability. On the basis of the data from reader 1, a second branch concerning biceps femoris tendon injury slightly optimized the dichotomization between both groups because a complete tear or osseous avulsion was found in only one patient in the anterior cruciate ligament (ACL) with posterolateral corner (PLC) group (ACL + PLC).

reports, we omitted arcuate ligament and only described distinct anatomic structures (5).

In a study with 22 patients, Collins et al (26) reported that ability to view the smaller structures (popliteofibular ligament, fabellofibular ligament, and popliteomeniscal fascicles) was not necessary to predict PLC instability; it was sufficient to assess the lateral collateral ligament, biceps femoris tendon, and popliteus tendon, which are viewable at MRI (3). To our knowledge, however, our study is the first that compared MRI findings between patients with and without posterolateral instability to determine the sensitivity, specificity, and accuracy of MRI findings. Our study included a control group that consisted of patients with acute ACL tears (instead of healthy control participants), which better reflects the actuality in clinical routine. Our decision tree analysis confirmed the observation made by Collins et al because lateral collateral ligament and biceps femoris tendon injuries were the most significant predictive findings for posterolateral instability. The sensitivity of a complete tear or fibular avulsion of the lateral collateral ligament for posterolateral instability was only moderate (reader 1, 52.6%; reader 2, 57.9%). Regarding the popliteus tendon, isolated complete tears are rare and were found in only two patients in our study, both of whom did not show posterolateral instability at clinical examination. All other complete popliteus tendon tears were accompanied by complete lateral collateral ligament tears.

There were significant differences between both groups in terms of bone marrow edema patterns. In the ACL with PLC group, edema was more frequent in the medial femoral condyle, consistent with previous reports (33,34). However, bone marrow edema was less frequent in the lateral tibial plateau, which may be explained by the typical trauma mechanism (varus force and hyperextension) leading to disruption rather than compression of the posterolateral structures. No statistically significant differences were found between the groups regarding the frequency of cortical compression fractures of the femoral condyle or tibial plateau.

Our study had limitations. First, this was a retrospective cohort study limited to patients who underwent ACL reconstruction. However, during the explored time interval, only one patient with reconstruction of an isolated posterolateral injury was found in the database (without ACL tear; not included in our study), which confirmed the rarity (34) of this injury pattern. Second, patients were included only when the time interval between trauma and MRI was 10 days or less to ensure that all findings were associated with acute trauma (eg, posterolateral fat pad edema or bone marrow edema). Third, the MRI protocol was not identical for all patients: two-thirds had undergone imaging at external institutions and were then referred to our institution for surgical treatment. However, only two patients had to be excluded because of incomplete

MRI protocol or insufficient image quality. Fourth, interobserver agreement was suboptimal for some imaging parameters. Nevertheless, only four of 162 (2.5%) patients were assigned to different subgroups between reader 1 and reader 2, which underlined the robustness of the applied decision tree analysis. Finally, our cross-sectional study design did not include follow-up data regarding ACL graft failure. Clinical examination is not a perfect reference standard and may have missed PLC instability in some patients. Furthermore, it is possible that some MRI findings may be indicative of higher subsequent ACL graft failure rates despite clinical testing negative for posterolateral instability at the time of surgery. Prospective longitudinal studies with long-term follow-up of graft failure rates will be necessary to test this hypothesis.

In conclusion, complete tear or fibular avulsion of the lateral collateral ligament was the most significant MRI predictor of posterolateral instability, followed by biceps femoris tendon tear. The assessment of smaller PLC structures (popliteofibular ligament, fabellofibular ligament, and popliteomeniscal fascicles) does not improve diagnostic performance of current MRI for the prediction of posterolateral instability.

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